

$(g_V^{\nu e})_{LRSM}$ and $(g_A^{\nu e})_{LRSM}$ in a Left-Right symmetric modelA. Gutiérrez-Rodríguez ¹, M. A. Hernández-Ruíz ¹ and M. Maya ²*(1) Facultad de Física, Universidad Autónoma de Zacatecas**Apartado Postal C-580, 98060 Zacatecas, Zacatecas México.**(2) Facultad de Ciencias Físico Matemáticas, Universidad Autónoma de Puebla**Apartado Postal 1364, 72000, Puebla, Puebla México.*

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Abstract

We start from a Left-Right Symmetric Model with massive Dirac neutrinos, with an electromagnetic structure that consists of a charge radius, and we calculate the cross-section of the scattering $\nu_\mu e^- \rightarrow \nu_\mu e^-$. Subsequently, we calculate the simultaneous contribution of the charge radius, of the additional Z_2 heavy gauge boson and of the mixing angle ϕ parameter of the model at the constants of couplings $(g_V^{\nu e})_{LRSM}$ and $(g_A^{\nu e})_{LRSM}$.

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I. INTRODUCTION

Neutrinos seem to be likely candidates for carrying features of physics beyond the Standard Model (SM) [1]. Apart from masses and mixings, charge radius, magnetic moments and electric dipole moments are also signs of new physics, and are of relevance in terrestrial experiments, the solar neutrino problem [2–5], astrophysics and cosmology [6,7].

At the present time, all the available experimental data for electroweak processes can be well understood in the context of the Standard Model of the electroweak interactions (SM) [1], except the results of the SUPER-KAMIOKANDE experiment on the neutrino mass [8]. However, Super-Kamiokande not is the only experiments in disagreement with the SM, also are includen at GALLEX, SAGE, GNO, HOMESTAKE and LSND [9]. Hence, the SM is the starting point for all the extended gauge models. In other words, any gauge group with physical sense must have as a subgroup the $SU(2)_L \times U(1)$ group of the standard model, in such a way that its predictions agree with those of the SM at low energies. The purpose of the extended theories is to explain some fundamental aspects which are not clarified in the framework of the SM. One of these aspects is the origin of the parity violation at the current energies. The Left-Right Symmetric Model (LRSM) based on the $SU(2)_R \times SU(2)_L \times U(1)$ gauge group [10] gives an answer to that problem, since it restores the parity symmetry at high energies and gives their violations at low energies as a result of the breaking of gauge symmetry. Detailed discussions on LRSM can be found in the literature [10–13].

Although in the framework of the SM, neutrinos are assumed to be electrically neutral. Electromagnetic properties of the neutrino are discussed in many gauge theories beyond the SM. Electromagnetic properties of the neutrino may manifest themselves in a magnetic moment of the neutrino as well as in a non vanishing charge radius, both making the neutrino subject to the electromagnetic interaction.

The present paper is an extension of previous work by one of the authors (M. Maya *et al.*), considering electromagnetic properties of the neutrino. In this work, we start from a Left-Right Symmetric Model (LRSM) with massive Dirac neutrinos left and right, with an

electromagnetic structure that consists of a charge radius and of an anomalous magnetic moment, and we calculated the cross-section of the scattering $\nu_\mu e^- \rightarrow \nu_\mu e^-$. The Feynman diagrams which contribute to the process $\nu_\mu e^- \rightarrow \nu_\mu e^-$ are shown in Fig. 1.

In previous papers [14], possible corrections at the couplings of the fermion with the gauge boson were calculated, in particular the couplings g_V and g_A of leptons with the neutral boson Z^0 , which have been measured with great precision in LEP and CHARM II [15]. In this work we calculate the simultaneous contribution of the charge radius, of the additional Z_R gauge boson and of the angle ϕ parameter of the LRSM at the constants of couplings $(g_V^{\nu e})_{LRSM}$ and $(g_A^{\nu e})_{LRSM}$. The charge radius in the LRSM considered is simply treated as a new parameter. One is thus dealing with a purely phenomenological analysis.

For an analysis of the electromagnetic form factors of the neutrino from a point of view theoretical in left-right models, see for example the Ref. [16].

This paper is organized as follows. In Sect. II we carry out the calculus of the process $\nu_\mu e^- \rightarrow \nu_\mu e^-$. In Sect. III we present the expressions for the constants of couplings $(g_V^{\nu e})_{LRSM}$ and $(g_A^{\nu e})_{LRSM}$. In Sect. IV we achieve the numerical computations. Finally, we summarize our results in Sect. V.

II. THE NEUTRINO-ELECTRON SCATTERING

We will assume that a massive Dirac neutrino is characterized by two phenomenological parameters, a magnetic moment μ_ν , expressed in units of the electron Bohr magnetons, and a charge radius $\langle r^2 \rangle$. Therefore, the expression for the amplitude \mathcal{M} of the process $\nu_\mu e^- \rightarrow \nu_\mu e^-$ due only to γ and Z^0 exchange, according to the diagrams depicted in Fig. 1 is given by

$$\mathcal{M}_\gamma = \bar{\nu}(k_2) \frac{\Gamma^\mu}{q^2} \nu(k_1) \bar{e}(p_2) \gamma_\mu e(p_1), \quad (1)$$

with

$$\Gamma^\mu = e F_1(q^2) \gamma^\mu - \frac{e}{2m_\nu} F_2(q^2) \sigma^{\mu\nu} q_\nu, \quad (2)$$

the neutrino electromagnetic vertex, where q is the momentum transfer and $F_{1,2}(q^2)$ are the electromagnetic form factors of the neutrino. Explicitly [3]

$$F_1(q^2) = \frac{1}{6}q^2\langle r^2 \rangle,$$

$$F_2(q^2) = -\mu_\nu \frac{m_\nu}{m_e},$$

where as already are mentioned $\langle r^2 \rangle$ is the neutrino mean-square charge radius and μ_ν the anomalous magnetic moment.

Furthermore

$$\begin{aligned} \mathcal{M}_{Z^0} = \frac{G_F}{\sqrt{2}} [& P\bar{\nu}(k_2)\gamma^\mu\nu(k_1)\bar{e}(p_2)\gamma_\mu e(p_1) + Q\bar{\nu}(k_2)\gamma^\mu\gamma_5\nu(k_1)\bar{e}(p_2)\gamma_\mu e(p_1) \\ & + R\bar{\nu}(k_2)\gamma^\mu\nu(k_1)\bar{e}(p_2)\gamma_\mu\gamma_5 e(p_1) + S\bar{\nu}(k_2)\gamma^\mu\gamma_5\nu(k_1)\bar{e}(p_2)\gamma_\mu\gamma_5 e(p_1)], \end{aligned} \quad (3)$$

where

$$\begin{aligned} P &= (a + 2b + c)g_V, \\ Q &= (-a + c)g_A, \\ R &= (-a + c)g_V, \\ S &= (a - 2b + c)g_A. \end{aligned} \quad (4)$$

The constants a , b and c [17] depend only of the parameters of the LRSM, and are

$$\begin{aligned} a &= (c_\phi - \frac{s_W^2}{r_W}s_\phi)^2 + \gamma(\frac{s_W^2}{r_W}c_\phi + s_\phi)^2, \\ b &= (c_\phi - \frac{s_W^2}{r_W}s_\phi)(-\frac{c_W^2}{r_W}s_\phi) + \gamma(\frac{s_W^2}{r_W}c_\phi + s_\phi)(\frac{c_W^2}{r_W}c_\phi), \\ c &= (\frac{c_W^2}{r_W}s_\phi)^2 + \gamma(\frac{c_W^2}{r_W}c_\phi)^2, \\ \gamma &= (\frac{M_{Z_1}}{M_{Z_2}})^2 = (\frac{M_{Z_L}}{M_{Z_R}})^2, \end{aligned} \quad (5)$$

where M_{Z_1} and M_{Z_2} are the masses of the neutral bosons that participate in the interaction. γ together with ϕ are the two new parameters that are introduced in the LRSM. While $g_V = -\frac{1}{2} + 2\sin^2\theta_W$ and $g_A = -\frac{1}{2}$, according to the experimental data [18].

The square of the amplitude is obtained by sum over spin states of the final fermions, so

$$\sum_{sp} |\mathcal{M}_T|^2 = \sum_{sp} (|\mathcal{M}_\gamma|^2 + |\mathcal{M}_{Z^0}|^2 + \mathcal{M}_{Z^0} \mathcal{M}_\gamma^\dagger + \mathcal{M}_{Z^0}^\dagger \mathcal{M}_\gamma), \quad (6)$$

where:

$$\sum_{sp} |\mathcal{M}_\gamma|^2 = \frac{8}{9} e^4 \langle r^2 \rangle^2 E^4 (5 + 2x + x^2), \quad (7)$$

$$\begin{aligned} \sum_{sp} |\mathcal{M}_{Z^0}|^2 = & 16 G_F^2 E^4 [(P^2 + Q^2 + R^2 + S^2)(5 + 2x + x^2) \\ & + 2(P S + Q R)(3 - 2x - x^2)], \end{aligned} \quad (8)$$

$$\sum_{sp} (\mathcal{M}_{Z^0} \mathcal{M}_\gamma^\dagger + \mathcal{M}_{Z^0}^\dagger \mathcal{M}_\gamma) = \frac{32}{3\sqrt{2}} e \langle r^2 \rangle G_F E^4 [5P + 3S + (P - S)(2x + x^2)], \quad (9)$$

and $x = \cos \theta$, with θ the scattering angle.

In the expressions (7), (8) and (9) it is observed that there is no contribution of the anomalous magnetic moment; this is due to the fact that the magnetic moment induces change of helicity, which is not considered here. However, there is contribution of the electroweak charge radius, of the heavy gauge boson Z_R and of the mixing angle ϕ .

The scattering cross-section in the center of mass system (where s is the square of the center-of-mass energy) is given by

$$\sigma = \int \frac{d\Omega}{64\pi^2 s} \frac{1}{2} \sum_{sp} |\mathcal{M}_T|^2, \quad (10)$$

where the square of the total amplitude of transition $\sum_{sp} |\mathcal{M}_T|^2$ is given in the Eq. (6).

We write the total cross-section and the interference cross-section of the reaction $\nu_\mu e^- \rightarrow \nu_\mu e^-$ in the laboratory system using the relation [18]

$$\frac{E^4}{s} = \frac{m_e E_{lab}}{8}, \quad (11)$$

we obtain the following

$$\begin{aligned} \sigma_T^{LRSM} = & \frac{G_F^2 m_e E_\nu}{2\pi} \left\{ 2\mathcal{R}^2 + 2\mathcal{R}(P + S) + \frac{(P + S)^2 + (Q + R)^2}{2} \right. \\ & \left. + \frac{1}{3} [2\mathcal{R}^2 + 2\mathcal{R}(P - S) + \frac{(P - S)^2 + (Q - R)^2}{2}] \right\}, \end{aligned} \quad (12)$$

while for the interference:

$$\sigma_{\gamma Z^0}^{LRSM} = \frac{2G_F^2 m_e E_\nu}{3\pi} \mathcal{R}(2P + S), \quad (13)$$

where

$$\mathcal{R} = \frac{\sqrt{2}\pi\alpha}{3G_F} \langle r^2 \rangle, \quad (14)$$

is defined, and $\alpha = \frac{e^2}{4\pi}$ is the fine-structure constant. P, Q, R and S are defined in Eq. (4) and to be in terms of the LRSM parameters (ϕ, M_{Z_R}) . Let us rewrite the interference cross-section of the following form:

$$\begin{aligned} \sigma_{\gamma Z^0}^{LRSM} = & K \langle r^2 \rangle (2g_V + g_A) \left[\left\{ 1 + \left(\frac{2g_V a_W + g_A b_W}{2g_V + g_A} \right) \gamma \right\} c_\phi^2 \right. \\ & \left. + \left\{ 1 + \left(\frac{2g_V a_W + g_A b_W}{2g_V + g_A} \right) \gamma \right\} s_\phi^2 + (\gamma - 1) \left(\frac{2g_V + g_A b'_W}{2g_V + g_A} \right) s_\phi c_\phi \right], \end{aligned} \quad (15)$$

where

$$K = \frac{4G_F m_e \alpha E_\nu}{9\sqrt{2}},$$

and

$$a_W = \frac{(s_W^2 + c_W^2)^2}{r_W^2}, \quad b_W = \frac{(s_W^2 - c_W^2)^2}{r_W^2}, \quad b'_W = \frac{2(s_W^2 - c_W^2)}{r_W},$$

the contribution of the new heavy boson Z_R in each term of the Eq. (15) stays patent. In the limit $M_{Z_R} \rightarrow \infty$, $\gamma \rightarrow 0$ and $\phi = 0$ one has the charge radius that is denoted by $\langle r^2 \rangle_0$, and the interference cross-section is

$$\sigma_{\gamma Z^0}^0 = K \langle r^2 \rangle_0 (2g_V + g_A), \quad (16)$$

which agrees with the term of interference of the Ref. [3,7]. Here $\langle r^2 \rangle_0$ is the charge radius inside of the SM minimally extended to include massive Dirac neutrinos, with an electromagnetic structure.

III. THE VECTOR-AXIAL COUPLINGS

At the present time, the most precise direct determinations of $g_{V,A}^{\nu e}$ come from the CHARM II experiment using $\nu_\mu e^-$ scattering [15] $g_V^{\nu e} = -0.035 \pm 0.017$ and $g_A^{\nu e} =$

-0.503 ± 0.017 at 1σ , in agreement with the SM. In this section, we obtain expressions for $(g_V^{\nu e})_{LRSM}$ and $(g_A^{\nu e})_{LRSM}$ in terms of the SM couplings g_V^{SM} and g_A^{SM} , of the electroweak charge radius, the mixing angle ϕ parameter of the LRSM and of the heavy boson Z_R . Returning to the expression of the total cross-section Eq. (12) and defined

$$P = f_1 g_V^{\nu e}, \quad Q = -f_2 g_V^{\nu e}, \quad R = -f_2 g_A^{\nu e}, \quad S = f_3 g_A^{\nu e},$$

we obtain

$$\begin{aligned} \sigma_T^{LRSM} = \frac{G_F^2 m_e E_\nu}{2\pi} & \left\{ \mathcal{R}^2 + 2\mathcal{R}(f_1 g_V^{\nu e} + f_3 g_A^{\nu e}) + \frac{1}{2}(f_1 g_V^{\nu e} + f_3 g_A^{\nu e})^2 + \frac{1}{2}f_2^2 (g_V^{\nu e} + g_A^{\nu e})^2 \right. \\ & \left. + \frac{1}{3}[\mathcal{R}^2 + 2\mathcal{R}(f_1 g_V^{\nu e} - f_3 g_A^{\nu e}) + \frac{1}{2}(f_1 g_V^{\nu e} - f_3 g_A^{\nu e})^2 + \frac{1}{2}f_2^2 (g_V^{\nu e} - g_A^{\nu e})^2] \right\}, \end{aligned} \quad (17)$$

where

$$f_1 = u^2 + \frac{v^2}{r_W^2} \gamma, \quad f_2 = uv(1 - \gamma), \quad f_3 = v^2 + u^2 r_W^2 \gamma, \quad (18)$$

and

$$u = \cos \phi - \frac{\sin \phi}{r_W}, \quad v = \cos \phi + r_W \sin \phi$$

with \mathcal{R} and γ as defined in the Eqs. (5) and (14).

The total cross-section for the reaction $\nu_\mu e^- \rightarrow \nu_\mu e^-$ in the context of the SM [18] is

$$\sigma^{SM} = \frac{G_F^2 m_e E_\nu}{2\pi} \{ (g_V^{\nu e} + g_A^{\nu e})^2 + \frac{1}{3} (g_V^{\nu e} - g_A^{\nu e})^2 \},$$

likewise we have

$$\sigma_T^{LRSM} = \frac{G_F^2 m_e E_\nu}{2\pi} \{ ((g_V^{\nu e})_{LRSM} + (g_A^{\nu e})_{LRSM})^2 + \frac{1}{3} ((g_V^{\nu e})_{LRSM} - (g_A^{\nu e})_{LRSM})^2 \}. \quad (19)$$

From Eqs. (17) and (19), the couplings $(g_V^{\nu e})_{LRSM}$ and $(g_A^{\nu e})_{LRSM}$ in terms of the couplings of the SM and of the LRSM parameters are

$$(g_V^{\nu e})_{LRSM} = \mathcal{R} f_3 + \frac{1}{2} (f_1 f_3 + f_2^2) g_V^{SM}, \quad (20)$$

$$(g_A^{\nu e})_{LRSM} = \{ \mathcal{R} f_3 + \frac{1}{2} (f_1 f_3 + f_2^2) \} g_A^{SM}. \quad (21)$$

In these expressions, in the limit when $M_{Z_R} \rightarrow \infty$, $\gamma \rightarrow 0$ and $\phi = 0$, the couplings of the SM are recovered.

IV. RESULTS

In this section numerical results obtained by using the SM of the electroweak interaction [1] are presented. We take $M_{Z_L} = 91.187 \pm 0.007 \text{ GeV}$, $\sin^2 \theta_W = 0.2312$ and $g_V = -\frac{1}{2} + 2 \sin^2 \theta_W$, $g_A = -\frac{1}{2}$ according to the experimental data [18].

The reported bounds for M_{Z_R} [14,15,18,19] indicate that this is not less than 100 GeV . We have chosen $M_{Z_R} \leq 800 \text{ GeV}$ to estimate the contribution of the additional heavy boson M_{Z_R} .

In Fig. 2 we have plotted $(g_V^{\nu e})_{LRSM}$ from Eq. (20), as a function of the LRSM parameters. We take $\phi = 0$, $\mathcal{R} < 0.02$ [15] and we choose $M_{Z_R} \leq 800 \text{ GeV}$. In this figure we observed that the experimental value $g_V^{exp} = -0.052$ is reached for small values of \mathcal{R} and large values of M_{Z_R} . We obtain $-0.02 \leq (g_V^{\nu e})_{LRSM} \leq -0.05$ at the 90 % C. L..

In Fig. 3 we have plotted $(g_A^{\nu e})_{LRSM}$ from Eq. (21) as a function of \mathcal{R} and M_{Z_R} . The range of variation for the LRSM parameters is the same as in Fig. 2. In this case the experimental data, $g_A^{exp} = -0.52$, is reached for large values of \mathcal{R} and M_{Z_R} . We obtain $-0.5 \leq (g_A^{\nu e})_{LRSM} \leq -0.515$ at the 90 % C. L..

Fig. 4 shows the effective coupling $(g_V^{\nu e})_{LRSM}$ as a function of the LRSM parameters ϕ and M_{Z_R} . According to the experimental data, the allowed range for the mixing angle between Z_L^0 and Z_R^0 is $-0.009 \leq \phi \leq 0.004$ with a 90 % C.L. [19–21], we choose $M_{Z_R} \leq 800$ where ϕ is measured in radians and M_{Z_R} in GeV . In the figure it is observed that the experimental data $g_V^{exp} = -0.052$ is reached for small values of ϕ and M_{Z_R} , while the SM data $g_V^{SM} = -0.038$ is reached for large values of ϕ and M_{Z_R} . We obtain $-0.039 \leq (g_V^{\nu e})_{LRSM} \leq -0.044$ at the 90 % C. L.. Fig. 5 shows the coupling $(g_A^{\nu e})_{LRSM}$ as a function of ϕ and M_{Z_R} . The range of variation for the LRSM parameters is the same as in Fig. 4. In this case the experimental data $g_A^{exp} = -0.52$ is reached for small values of ϕ and M_{Z_R} , and the data SM $g_V^{SM} = -0.5$ is reached for large values of both parameters. We obtain $-0.497 \leq (g_A^{\nu e})_{LRSM} \leq -0.51$ at the 90 % C. L..

Figs. 6 and 7 show the contribution of the LRSM parameters at the non-standard

couplings $(g_V^{\nu e})_{LRSM}$ and $(g_A^{\nu e})_{LRSM}$ to $M_{Z_R} = 410 \text{ GeV}$ [14,15,18,19] and $0 \leq \mathcal{R} \leq 0.02$, $-0.009 \leq \phi \leq 0.004$. In the first case, the experimental result for g_V is obtained for large \mathcal{R} and ϕ , while for g_A the data experimental is obtained for small \mathcal{R} and ϕ . In this case we obtain $-0.028 \leq (g_V^{\nu e})_{LRSM} \leq -0.05$ and $-0.493 \leq (g_A^{\nu e})_{LRSM} \leq -0.51$ at the 90 % C. L..

V. CONCLUSIONS

In summary, we have determined an expression for (a) total cross-section; (b) non-standard $\nu_\mu e^-$ vector and axial couplings. In case (a), we find that for the cross-section of interference Eq. (15), the contribution of the new boson M_{Z_R} is evident. The SM prediction is obtained when we take the limit $M_{Z_R} \rightarrow \infty$, $\gamma \rightarrow 0$ and $\phi = 0$ obtaining the Eq. (16), which agrees with the term of interference report in the literature Ref. [3,7].

In case (b), the non-standard couplings $(g_A^{\nu e})_{LRSM}$ and $(g_V^{\nu e})_{LRSM}$ Figs. 2-7 are affected very sensitively by the LRSM parameters as well as for the charge radius $\langle r^2 \rangle$ which is implicit in the parameter \mathcal{R} . Our conclusion is that the experimental value of the coupling g_V favours small values of \mathcal{R} , while the coupling g_A points at large values of \mathcal{R} .

In this paper we point out the importance of continuing to examine the $\nu_\mu e^-$ scattering using a Left-Right Symmetric Model and assuming that a massive Dirac neutrino is characterized by two phenomenological parameters, a magnetic moment μ_ν , and a charge radius $\langle r^2 \rangle$. It is also necessary to bear in mind that the sensitivity of the experiment is increased, which must occur in a next generation of accelerators or of a perfection of the current detectors (SUPER-KAMIOKANDE) [8], and arguments are also given which make us think that experiments with reactors as radioactive sources of neutrinos such as the BOREXINO detector [22] and the reactor MUNU [23] can give answers to the question of the charge radius, non-standard vector-axial couplings and other parameters.

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FIGURE CAPTIONS

Fig. 1 The Feynman diagrams contributing to the process $\nu_\mu e^- \rightarrow \nu_\mu e^-$, in a left-right symmetric model.

Fig. 2 Plot of $(g_V^{\nu e})_{LRSM}$ as a function of the LRSM parameters $0 \leq \mathcal{R} \leq 0.02$, $M_{Z_R} \leq 800$ GeV with $\phi = 0$.

Fig. 3 Plot of $(g_A^{\nu e})_{LRSM}$ as a function of the LRSM parameters $0 \leq \mathcal{R} \leq 0.02$, $M_{Z_R} \leq 800$ GeV with $\phi = 0$.

Fig. 4 Same as in Fig. 2, but with $-0.009 \leq \phi \leq 0.004$, $M_{Z_R} \leq 800$ GeV and $\mathcal{R} = 0.018$.

Fig. 5 Same as in Fig. 3, but with $-0.009 \leq \phi \leq 0.004$, $M_{Z_R} \leq 800$ GeV and $\mathcal{R} = 0.018$.

Fig. 6 Same as in Fig. 2, but with $-0.009 \leq \phi \leq 0.004$, $0 \leq \mathcal{R} \leq 0.02$ and $M_{Z_R} = 410$ GeV .

Fig. 7 Same as in Fig. 3, but with $-0.009 \leq \phi \leq 0.004$, $0 \leq \mathcal{R} \leq 0.02$ and $M_{Z_R} = 410$ GeV .

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